IMPROVED PATTERN GENERATOR

Field of the invention

The present invention relates to printing of patterns with extremely high precision on photosensitive surfaces, such as photomasks for semiconductor devices and displays. It also relates to direct writing of semiconductor device patterns, display panels, integrated optical devices and electronic interconnect structures. Furthermore, it can have applications to other types of precision printing such as security printing. The term printing should be understood in a broad sense, meaning exposure of photoresist and photographic emulsion, but also the action of light on other light sensitive media such as dry-process paper, by ablation or chemical processes activated by light or heat. Light is not limited to mean visible light, but a wide range of wavelengths from infrared (IR) to extreme UV. Of special importance is the ultraviolet range from 370 nm (UV) through deep ultraviolet (DUV), vacuum ultraviolet (VUV) and extreme ultraviolet (EUV) down to a few nanometers wavelength. EUV is in this application defined as the range from 100 nm and down as far as the radiation is possible to treat as light. A typical wavelength for EUV is 13 nm. IR is defined as 780 nm up to about 20 μm.

In a different sense the invention relates to the art and science of spatial light modulators and projection displays and printers using such modulators. In particular it improves the grey-scale properties, the image stability through focus and image uniformity and the data processing for such modulators by application of analog modulation technique. The most important use of the analog modulation is to generate an image in a high-contrast material such as photoresist with an address grid, i.e. the increment by which the position of an edge in the pattern is specified, that is much finer than the

grid created by the pixels of the spatial light modulator.

Background of the invention

5   It is known in the current art to build precision pattern generators using projection of micromirror spatial light modulators (SLMs) of the micromirror type (Nelson 1988, Kück 1990). To use an SLM in a pattern generator has a number of advantages compared to the more
10   wide-spread method of using scanning laser spots: the SLM is a massively parallel device and the number of pixels that can be written per second is extremely high. The optical system is also simpler in the sense that the illumination of the SLM is non-critical, while in a laser
15   scanner the entire beam path has to be built with high precision. Compared to some types of scanners, in particular electrooptic and acoustooptic ones, the micromirror SLM can be used at shorter wavelengths since it is a purely reflective device.
20   In both references cited above the spatial modulator uses only on-off modulation at each pixel. The input data is converted to a pixel map with one bit depth, i.e. with the values 0 and 1 in each pixel. The conversion can be done effectively using graphic processors or custom logic
25   with area fill instructions.

       In a previous application by the same inventor Sandström (Sandström et. al. 1990), the ability to use an intermediate exposure value at the boundary of a pattern element to fine-adjust the position of the element's edge
30   in the image created by a laser scanner was described.

       It is also known in the art to create a grey-scale image, preferably for projection display of video images and for printing, with an SLM by variation of the time a pixel is turned on or by printing the same pixel several
35   times with the pixel turned on a varying number of times. The present invention devices a system for direct grey-scale generation with a spatial light modulator, with a

special view to the generation of ultra-precision patterns. Important aspects in the preferred embodiments, are uniformity of the image from pixel to pixel and independence of exact placement of a feature relative to

5   the pixels of the SLM and stability when focus is changed, either with intention or inadvertently.

Summary of the invention

It is therefore an object of the present invention
10   to provide an improved pattern generator for printing of precision patterns.

This object is achieved with an apparatus according to the appended claims, providing an analog modulation of the pixels in the SLM.

15

Brief description of the drawings

Figure 1 shows a printer in prior art. The SLM consists of micromirrors that deflect the light from the lens pupil.

20   Figure 2 shows a number of pixel designs with the upper four pixels in an off state and the remaining five pixels turned on.

Figure 3 shows an array of pixels moving up and down like pistons, thereby creating a phase difference. This

25   is how an edge can be fine-positioned with a phase-type SLM.

Figure 4 shows a schematic comparison between an SLM with deflecting mirrors and an SLM with deforming mirrors.

30   Figure 5 shows a flow diagram of a method for translating and feeding data to the SLM.

Figure 6 shows a preferred embodiment of a pattern generator according to the invention.

Figure 7 shows schematically possible complex
35   amplitudes for different types of SLM.

Figure 8 shows schematically different types of controlling of the SLM mirrors.

Description of the invention

The basis for understanding the invention is the
generic arrangement in Figure 1 which shows a generic
5   projection printer with an SLM. Spatial light modulators
based on reflection come in two varieties, the deflection
type (Nelson) and the phase type (Kück). The difference
between them may in a particular case with micromirrors
seem small, but the phase SLM extinguishes the beam in
10 the specular direction by destructive interference, while
a pixel in a deflection SLM deflects the specular beam
geometrically to one side so that it misses the aperture
of the imaging lens as shown in figure 1. For ultra-
precise printing as performed in the current invention
15 the phase-modulating system as described by Kück 1990 is
superior to the deflecting type. First, it has better
contrast since all parts of the surface, also hinges and
support posts, take part in the destructive interference
and total extinction can be achieved. Second, a system
20 that works by deflecting the light to the side is
difficult to make symmetrical around the optical axis at
intermediate deflection angles, creating a risk of
feature instability when focus is changed. In the
preferred embodiments the phase type is used, but if one
25 accepts or designs around the asymmetry of the deflection
type it could also be used. This is illustrated
schematically in fig 4. In the first figure, 4a, a non-
deflected micromirror 401 is illuminated, and the
reflected light is not directed towards the aperture 402,
30 and, hence, the light does not reach the substrate 403.
In fig 4b, on the other hand, the mirror is fully
deflected, and all the reflected light are directed
towards the apperture. In an intermediate position only
part of the reflected light will reach the substrate,
35 which is shown in fig 4c. However, in this case the light
is not symmetrical around the optical axis for the lens
404, and there is an oblique incidence on the substrate.

Hereby the distance between the lens and the substrate area becomes very critical, and small changes, such as the one being indicated by the dashed position for area, causes significant displacements of the features on the

5   substrate. A way to solve this problem is indicated by the fig 4d-f. Here, a first exposure is made with a first deflection angle for the micromirror, and thereafter a second exposure, preferably with the same light dose, is made for a second deflection angle, being complementary

10 to the first angle. Hereby, the combination of the first and second exposure is symmetrical around the optical axis for the lens. Another way to solve the problem is to use deforming mirror 401', such as is shown in fig 4g, whereby the reflected light is evenly distributed over

15 aperture. This last figure could schematically represent two cases, a phase type SLM (described below) or a deflection SLM, where light is reflected from different parts of the mirror.

The phase SLM can be built either with micromachined

20 mirrors, so called micromirrors, or with a continuous mirror surface on a supporting substrate that is possible to deform using an electronic signal. In Kück 1990 a viscoelastic layer controlled by an electrostatic field is used, but it is equally possible, especially for very

25 short wavelengths where deformations of the order of a few nanometer are sufficient, to use a piezoelectric solid disk that is deformed by electric field or another electrically, magnetically or thermally controlled reflecting surface. For the remainder of this application

30 an electrostatically controlled micromirror matrix (one- or two-dimensional) is assumed, although other arrangements as described above are possible, such as transmissive or reflecting SLMs relying on LCD crystals or electrooptical materials as their modulation

35 mechanism, or micromechanical SLMs using piezoelectric or electrostrictive actuation.

The invention preferably uses a micromirror where the phase modulation is variable to obtain a variable amount of light reaching the pupil of the projection lens. Figure 2 shows some multi-element mirrors. The

5   tilts of the various parts of the mirrors are unimportant. In fact one element by itself would direct the light toward the lens while another would direct it outside of the pupil. The correct way to understand the function is to look at the complex amplitude reaching the

10   center of the pupil from each infinitesimal area element of the mirror and integrate the amplitude over the mirror. With a suitable shape of the mirror it is possible to find a deformation where the complex amplitudes add up to almost zero, corresponding to no

15   light reaching the pupil. This is the off-state of the micromirror, while a relaxed state where the mirror surface is flat and the complex amplitudes add in phase is the on-state. Between the on and off-states the amount of light in the specular direction is a continuous but

20   non-linear function of the deformation.

The pattern to be written is normally a binary pattern, such as a photomask pattern in chrome on a glass substrate. In this context binary means that there are no intermediate areas: a certain point on the photomask

25   surface is either dark (covered with chrome) or clear (no chrome). The pattern is exposed in photoresist by the projected image from the SLM and the photoresist is developed. Modern resists have high contrast, meaning that a small percentage change in exposure makes the

30   difference between full removal of the resist in the developer and hardly any removal at all. Therefore the photoresist has an edge that is normally almost perpendicular to the substrate surface, even though the aerial image has a gradual transition between light and

35   dark. The chrome etching does further increase the contrast, so that the resulting image is perfectly

binary: either opaque or clear with no intermediate
areas.

The input data is in a digital format describing the
geometry of the pattern to be written on the surface. The
5   input data is often given in a very small address unit,
e.g. 1 nanometer, while setting pixels in the SLM to
either on or off gives a much coarser pattern. If a pixel
on the SLM is projected to a 0.1 μm pixel in the image, a
line can only have a width that is an integer number of
10   pixels (n * 0.1 μm where n is an integer). An address
grid of 0.1 μm was enough until recently, but the advent
of so called optical proximity correction OPC makes a
grid of 1 - 5 nanometers desirable. In OPC the size of
features in the mask are modified slightly to compensate
15   for predicted optical image errors when the mask is used.
As an example, when a mask with four parallel lines 0.8
μm wide is printed in a modern 4X reduction stepper (a
projection printer for semiconductor wafers) they will in
a typical case print as lines 0.187, 0.200, 0.200, and
20   0.187 μm wide although they were intended to have the
same width. This can be predicted by simulation of the
image formation and the user of the mask may use OPC to
compensate in the mask. therefore he wants the first and
last line in the mask to be 4 * 0.213 = 0.852 μm instead
25   of 0.800 μm. With an address grid of 0.1 μm he cannot
make the correction, but with 5 nm address grid or finer
such correction are possible.

In figure 5 the method for providing data for the
SLM is shown in a flow diagram. The first step, S1, is to
30   divide the pattern data for the pattern to be written
into separate pattern fields. The pattern data is
preferably received in digital form. Thereafter, in step
S2, the fields are rasterised, and thereby assigned
different exposure values. These values are then
35   corrected for nonlinear response, step S3, and pixel-to-
pixel variations, step S4. Finally, the pixel values are
converted to drive signals and forwarded to the SLM.

The invention preferably uses intermediate values
between the off-state and on-state to create a fine
address grid, e.g. 1/15, 1/25, 1/50, of the size of a
pixel. A printed feature consists of pixels in the on
5   state, but along the edge it has pixels set to
intermediate values. This is done by driving the pixels
with other voltages than the on and off voltages. Since
there are several cascaded non-linear effects (the
position of the edge versus exposure at the pixels at the
10   boundary, the exposure vs. the deformation, and the
deformation vs. the electric field) a non-linear
transformation from the input data to the electric field
is needed. Furthermore this transformation is calibrated
empirically at regular time intervals.

15   Figure 3 shows an array of pixels moving up and down
like pistons, thereby creating a phase difference. The
figure shows how the pixels are controlled to create the
reflectivity in the inset. The bright areas have pixels
with 0 phase, while dark areas are created by pixels with
20   alternating +90 and -90 degree phase. The oblique
boundaries between bright and dark areas are created by
intemediate values of phase. This is how an edge can be
fine-positioned with a phase-type SLM. However, other
types of SLM with intermediate values could be used in
25   the same manner. The imaging properties with the phase
SLM driven into intermediate values are complex and it is
far from obvious that the edge will be moved in figure 3.
However, it has been shown by extensive theoretical
calculations and experiments by the inventor, that the
30   described effect is real.

To create a finer address grid the electronic
processing system is adapted to create one type of pixel
map inside pattern features, another type of pixel map
outside features, and intermediate pixel maps at a
35   boundary, as shown in Figure 3, where the intermediate
pixel map at a boundary is generated in dependence of the
placement of the boundary in a grid finer than that of

the pixels of the SLM projected on the workpiece. The SLM
and the projection system creates one exposure level
inside features, another exposure level between features,
and an intermediate exposure level at the boundary. The
5   intermediate exposure level is created using the
capability of the SLM to modulate to multiple states.
The response from driving signals to actual placement of
the boundary is characterized and corrected for. It is
empirically measured and a calibrating function is
10 computed and stored in the data processing and delivery
system.

        To further improve the address resolution the stage
and the SLM are adapted to stitching exposure fields
together along a direction not parallel to the coordinate
15 system of the SLM, typically 45 degrees. In particular
the continuous movement of the stage or optical system
takes place in a direction not parallel to the SLM, but
typically at 45 degrees from the coordinate system of the
SLM. It is also possible to have an SLM with non-
20 orthogonal axises, in which case it is advantageous to
have no axis parallel to the direction of motion.
Furthermore, to suppress line errors resulting from
imperfections in the column and row drivers of the SLM of
line error in the matrix itself it is effective to have
25 the row and column lines at an angle to the direction of
stitching, i.e. the vector between the centers of
stitched fields.
Additional refinement of the address grid is created by
the overlaying of at least two exposures with modified
30 data such that the combined exposure has intermediate
values not possible to obtain in a single exposure.

        The design of the phase-type SLM
        A cloverleaf mirror design, shown in fig 2c, as used
35 in prior art is possible to drive to intermediate states
between on and off states. However, when the integrated
complex amplitude is plotted as a function of deflection,

it is seen that it never goes to zero completely but
circles around zero, therefore having a non-zero minimum
reflectivity with a varying phase angle. This is shown
schematically by the line 701 in fig 7, where 703

5   indicates a position for a certain deformation value, and
φ being the associated phase angle. A thorough analysis
of an image with some pixels set to intermediate states
shows that the position of the edges in the final image
are not stable through focus if the integrated phase

10 angle of the edge pixels is not zero. This is the
diffraction effect analogous to the specular one shown in
fig 4. In a preferred embodiment of the invention a new
type of pixels with pivoting elements is used. Examples
of such elements are shown in fig 2e-h. When the elements

15 pivots one end moves toward the light source and the
other end away from it thereby keeping the average phase
close to zero. This is shown schematically by the dashed
line 702 in fig 7. Furthermore the cloverleaf design has
a problem of built-in stress created during the

20 fabrication. This stress tends to give a partial
deformation without an applied electric field. The built-
in deformation is not perfectly the same in every pixel
since it depends on imperfections during the
manufacturing. In the cloverleaf design this difference

25 from pixel to pixel creates a first-order variation of
reflectivity. With pixel cells built from pivoting
elements the same effect occurs, but gives a second-order
effect. Therefore the uniformity is better in the
projected image.

30   The design of the modulating elements and the
exposure method are adapted to creating, for differently
placed and/or differently oriented edges in the pattern,
a symmetry in the aperture stop of the projection system.
Inherent assymmetries between edges placed at different

35 positions relative to the pixel grid can be reduced by
overlaying at least two images with different placement
of the pixel grid relative to the pattern.

For a deflection type of SLM the symmetry relates to
the intensity distribution in the aperture stop. Best is
to have modulating elements that deflect the light
symmetrically relative to the center of the aperture
5   stop, or else can overlayed exposures with complementary
deflection be used to create symmetry. With modulating
elements with steerable deflection it is possible to
create a constant geometrical realtion between the
deflection at a pixel at an edge and the edge, i.e.
10   directing it in a direction perpendicular to the edge and
toward the interior of the feature.

With a diffraction type SLM it is possible to create
symmetry by overlaying exposures with opposite phase
maps. Symmetry can be maintained if the complex amplitude
15   is everywhere real on the SLM, and pixels can be designed
with the integrated complex amplitude being essentiall
real with values in the range -1 to 1. Many times it is
sufficient with amplitudes in the range -0.5 to 1. This
is the case with the square pivoting micromirror elements
20   in Figure 2e,f,g,h.

With access to a small negative amplitude to print
in the background areas it is possible for enhance the
resolution. In a more complex scheme it is possible to
drive groups of adjacent pixels to combine in the image,
25   and after being filtered by the imaging system, to give a
desired real amplitude.

In order to preserve symmetry it is beneficial to
have at least 2-fold symmetry and preferrably 4-fold.
Symmetry can be created for pixels not having an inherent
30   rotational symmetry by muple overlayed exposures.
Furthermore, with a pixel design or exposure sequence
giving a controlled real amplitude can be used for
resolution enhancements. Dark lines can be given extra
contrast if placed between areas with opposite phase and
35   the edge of a feature can be improved by driving adjacent
pixels inside the feature to higher positive amplitudes
or adjacent pixels outside to negative ones.

Image enhancements.

There is a third advantage with a pivoting design: the cloverleaf does not reach full extinction, but a

5 pivoting cell can more easily be given a geometry that gives full extinction, or even goes through zero and comes back to a small non-zero reflection, but with reversed phase. With better extinction there is greater freedom to print overlapping exposures, designing for a

10 small negative value 702 gives better linearity close to extinction. Printing with a weak exposure, approximately 5%, in the dark areas, but with reversed phase can give an increased edge sharpness of 15 - 30 % and the ability to print smaller features with a given lens. This is an

15 analog to so called attenuating phase-shifting masks that are used in the semiconductor industry. A related method of increasing the edge acuity is to set the pixels that are inside a feature a lower value and those near the edge a higher value. This gives a new type of image

20 enhancement not possible with current projection of patterns from masks or by the use of projectors following Nelson and Kück. The combination of a non-zero negative amplitude in the background and an increased exposure along the edges need not conflict with the creation of a

25 fine address grid by driving edge pixels to intermediate values, since the effects are additive or at least computable. When the pixels are substantially smaller than the feature to be printed there exists a combination of pixel values that creates all effects simultaneously.

30 To find them requires more computation than the generation of a fine address grid alone, but in some applications of the invention the ability to print smaller features can have a high value that pays for the extra effort.

35 In the case of a continuous mirror on a viscoelastic layer there is an inherent balancing of the average phase to zero. Simulations have shown that the driving to

intermediate values for fine positioning of feature edges
work also for the continuous mirror. The non-linearities
are smaller than with micromirrors. But for the method to
work well the minimum feature has to be larger than with
5   micromirrors, i.e. have a larger number of addressed
pixels per resolved feature element is needed.
Consequences are a larger SLM device and that for given
pattern the amount of data is larger. Therefore the
micromirrors have been chosen in a first and second
10   embodiment.

In the invention a pixel with rotation-symmetrical
deformation (at least two-fold symmetry, in a preferred
embodiment four-fold symmetry) is used for two reasons:
to give a symmetrical illumination of the pupil of the
15   projection lens and to make the image insensitive to
rotations. The latter is important for printing a random
logic pattern on a semiconductor wafer. If there is an x-
y asymmetry the transistors laid-out along the x axis
will have a different delay from those along the y axis
20   and the circuit may malfunction or can only be used at a
lower clock-speed. The two requirements of image
invariance through focus and symmetry between x and y
makes it very important to create and maintain symmetries
in the optical system. Symmetry can be either inherent or
25   it can be created by delibrate balancing of assymetric
properties, such as using multiple exposures with
complementary assymetric properties. However, since
multiple exposures lead to reduced through-put inherent
symmetrical layouts are strongly favoured.
30

Preferred embodiments

A first preferred embodiment is a deep-UV pattern
generator for photomasks using an SLM of 2048 x 512
35   micromirrors. The light source is an KrF excimer laser
with a pulsed output at 248 nanometers, pulse lengths of
approximately 10 ns and a repetition rate of 500 Hz. The

SLM has an aluminum surface that reflects more than 90%
of the light. The SLM is illuminated by the laser through
a beam-scrambling illuminator and the reflected light is
directed to the projection lens and further to the
5   photosensitive surface. The incident beam from the
illuminator and the exiting beam to the lens are
separated by a semitransparent beamsplitter mirror.
Preferably the mirror is polarisation-selective and the
illuminator uses polarised light, the polarisation
10 direction of which is switched by a quarter-wave plate in
front of the SLM. For x and y symmetry at high NA the
image must be symmetrically polarised and a second
quarter-wave plate between the beamsplitter and the
projection lens creates a circularly polarised image. A
15 simpler arrangement when the laser pulse energy allows it
is to use a non-polarising beamsplitter. The quarter-wave
plate after the second pass through the beamsplitter is
still advantageous, since it makes the design of the
beam-splitting coating less sensitive. The simplest
20 arrangement of all is to use an oblique incidence at the
SLM so that the beams from the illuminator and to the
projection lens are geometrically separated, as in figure
1.

The micromirror pixels are 20 x 20 μm and the
25 projection lens has a reduction of 200X, making on pixel
on the SLM correspond to 0.1 μm in the image. The lens is
a monochromatic DUV lens with an NA of 0.8, giving a
point spread function of 0.17 μm FWHM. The minimum lines
that can be written with good quality are 0.25 μm.
30 The workpiece, e.g. a photomask, is moved with an
interferometer-controlled stage under the lens and the
interferometer logic signals to the laser to produce a
flash. Since the flash is only 10 ns the movement of the
stage is frozen during the exposure and an image of the
35 SLM is printed, 204.8 x 51.2 μm large. 2 milliseconds
later the stage has moved 51.2 μm, a new flash is shot
and a new image of the SLM is printed edge to edge with

the first one. Between the exposures the data input
system has loaded a new image into the SLM, so that a
larger pattern is composed of the stitched flashes. When
a full column has been written the stage advances in the
5   perpendicular direction and a new row is started. Any
size of pattern can be written in way, although the first
preferred embodiment typically writes patterns that are
125 x 125 mm To write this size of pattern takes 50
minutes plus the time for movement between consecutive
10   columns.

Each pixel can be controlled to 25 levels (plus
zero) thereby interpolating the pixel of 0.1 μm into 25
increments of 4 nanometers each. The data conversion
takes the geometrical specification of the pattern and
15   translates it to a map with pixels set to on, off or
intermediate reflection. The datapath must supply the SLM
with 2048 * 512 * 500 words of data per second, in
practice 524 Mbytes of pixel data per second. In a
preferred embodiment the writable area is maximally 230 x
20   230 mm, giving up to 230 / 0.0512 = 4500 flashes maximum
in a column and the column is written in 4500 / 500 = 9
seconds. The amount of pixel data needed in one column is
9 x 524 = 4800 Mb. To reduce the amount of transferred
and buffered data a compressed format is used, similar to
25   the one in Sandström at al. 90, but with the difference
that a pixel map is compressed instead of segments with a
length and a value. A viable alternative is to create a
pixel map immediately and use commercially available
hardware processors for compression and decompression to
30   reduce the amount of data to be transferred and buffered.

Even with compression the amount of data in a full
mask makes it highly impractical to store pre-fractured
data on disk, but the pixel data has to be produced when
it is used. An array of processors rasterise the image in
35   parallel into the compressed format and transfer the
compressed data to an expander circuit feeding the SLM
with pixel data. In the preferred embodiment the

processors rasterise different parts of the image and
buffer the result before transmitting them to the input
buffer of the expander circuit.

5   *A second preferred embodiment*
        In a second preferred embodiment the laser is an ArF
excimer laser with 193 nm wavelength and 500 Hz pulse
frequency. The SLM has 3072 x 1024 pixels of 20 * 20 μm
and the lens has a reduction of 333X giving a projected
10   pixel of 0.06 μm. There are 60 intermediate values and
the address grid is 1 nanometer. The point spread
function is 0.13 μm and the minimum line 0.2 μm. The data
flow is 1572 Mbytes/s and the data in one column 230 mm
long is 11.8 Gb.
15   A third preferred embodiment is identical with the
second one except that the matrix of pixels is rotated 45
degrees and the pixel grid is 84 μm, giving a projected
pixel spacing along x and y of 0.06 μm. The laser is an
ArF excimer laser and the lens the reduction of 240.
20   Because of the rotated matrix the density of pixels in
the matrix is less and the data volume is half of the
previous embodiment but with the same address resolution.

        Laser flash to flash variations
25   The excimer laser has two unwanted properties,
flash-to-flash energy variations of 5% and flash-to-flash
time gitter of 100 ns. In the preferred embodiments both
are compensated in the same way. A first exposure is made
of the entire pattern with 90% power. The actual flash
30   energy and time position for each flash is recorded. A
second exposure is made with nominally 10 % exposure and
with the analog modulation used to make the second
exposure 5 - 15% depending on the actual value of the
first one. Likewise a deliberate time offset in the
35   second exposure can compensate for the time gitter of the
first one. The second exposure can fully compensate the
errors in the first, but will itself give new errors of

the same type. Since it is only on average 10% of the total exposure both errors are effectively reduced by a factor of ten. In practice the laser has a time uncertainty that is much larger than 100 ns, since the
5 light pulse comes after a delay from the trigger pulse and this delay varies by a couple of microseconds from one time to another. Within a short time span the delay is more stable. Therefore the delay is measured continuously and the last delay values, suitably
10 filtered, are used to predict the next pulse delay and to position the trigger pulse.

It is possible to make corrections for stage imperfections in the same way, namely if the stage errors are recorded and the stage is driven with a compensating
15 movement in the second exposure. Any placement errors that can be measured can in principle be corrected in this way, partially or fully. It is necessary to have a fast servo to drive the stage to the computed points during the second exposure. In prior art it is known to
20 mount the SLM itself on a stage with small stroke and short response time and use it for fine positioning of the image. Another equally useful scheme is to use a mirror with piezoelectric control in the optical system between the SLM and the image surface, the choice between
25 the two is made from practical considerations. It is also possible to add a position offset to the data in an exposure field, and thereby move the image laterally.

The second exposure is preferably done with an attenuating filter between the laser and the SLM so that
30 the full dynamic range of the SLM can be used within the range 0 - 15 % of the nominal exposure. With 25 intermediate levels it is possible to adjust the exposure in steps of 15% * 1/25 = 0.6%.

The response varies slightly from pixel to pixel due
35 to manufacturing imperfections and, potentially, also from ageing. The result is an unwanted inhomogeneity in the image. Where image requirements are very high it may

be necessary to correct every pixel by multiplication
with the pixels inverse responsivity which is stored in a
lookup memory. Even better is the application of a
polynomial with two, three or more terms for each pixel.

5   This can be done in hardware in the logic that drives the
SLM.

In a more complex preferred embodiment several
corrections are combined into the second corrective
exposure: the flash to flash variation, flash time

10   gitter, and also the known differences in the response
between the pixels. As long as the corrections are small,
i.e. a few percent in each they will add approximately
linearly, therefore the corrections can be simply added
before they are applied to the SLM. The sum is multiplied

15   with the value desired exposure dose in that pixel.

Alternative illumination sources

The excimer laser has a limited pulse repetition
frequency (prf) of 500 - 1000 Hz depending on the

20   wavelength and type of the laser. This gives large fields
with stitching edges in both x and y. In two other
preferred embodiments the SLM is illuminated with a
pulsed laser with much higher prf, e.g. a Q-switched
upconverted solid state laser, and with a continuous

25   laser source scanned over the surface of the SLM, so that
one part of the SLM is reloaded with new data while
another part is printed. In both cases the coherence
properties of the lasers are different from the excimer
laser and a more extensive beam-scrambling and coherence

30   control is needed, e.g. multiple parallel light paths
with different pathlengths. In some implementations of
the invention the light output from a flash lamp is
sufficient and can be used as the light source.
Advantages are low cost and good coherence properties.

35   In the preferred embodiment with scanning
illumination two issues are resolved: the pulse to pulse
variation in time and energy, since the scanning is done

under full control preferably using an electrooptic
scanner such as acoustooptic or electrooptic, and many
continuous laser have less power fluctuation that pulsed
lasers. Furthermore the use of continuous lasers gives a
5   different selection of wavelengths and continuous lasers
are less dangerous to the eye than pulsed lasers. Most
important, however, is the possibility of reaching much
higher data rates with a matrix with only a few lines
since the scanning is non-critical and can be done with
10   100 kHz repetition rate or higher. Scanning the
illumination beam is also a way of creating a very
uniform illumination, which is otherwise difficult.

     In some embodiments it is possible, and feasible, to
use a flash lamp as the illumination source.
15

     EUV

     Light sources for EUV are based on radiation from a
particle accelerator, a magnetic plasma pinch machine or
the heating of a small drop of matter to extreme
20   temperatures with a high-power laser pulse. In either
case the radiation is pulsed. The EUV radiation
propagates only in vacuum and can only be focused by
reflective optics. A typical pattern generator using an
SLM has a small exposure field a modest requirement of
25   optical power. The design of the optical system is
therefore relaxed compared to that of an EUV stepper,
making it possible to use more mirrors and go to higher
NA than in a stepper. It is anticipated that a high-NA
lens will have a ring-shaped exposure field and it is
30   fully possible to adapt the shape of the SLM to such a
field. With a wavelength of 13 nm and an NA of 0.25 it is
possible to expose lines that are only 25 nm wide, and,
using image enhancement as described below, even below 20
nm. No other known writing technology can match this
35   resolution and a the same time the writing speed that is
made possible by the parallel character of an SLM.

Edge overlap

Since a two-dimensional field is printed for each
flash and the fields are stitched together edge to edge
to edge the stitching is very critical. A displacement of
5   only a few nanometers of one field will create pattern
errors along that edge that are visible and potentially
detrimental to the function of an electronic circuit
produced from the mask. An effective way of reducing the
unwanted stitching effects is to print the same pattern
10   in several passes but with a displacement of the
stitching boundaries between the passes. If the pattern
is printed four times the stitching error will occur in
four positions, but with only a fourth of the magnitude.
In a preferred embodiment of the current invention the
15   ability to create intermediate exposures is used together
with an overlap band between the fields. The values are
computed during the rasterisation, although it could also
be done during the expansion of the compressed data. Edge
overlap reduces the stitching errors with much less
20   throughput penalty than multipass printing.

Modified illumination

In the first preferred embodiment the illumination
of the SLM is done by an excimer laser and a light
25   scrambler such as a fly-eye lens array to create an
illumination that resembles that from a circular self-
luminous surface in the pupil plane of the illuminator.
In order to increase the resolution when printing with a
specific projection system it is possible to use a
30   modified illumination. In the most simple cases pupil
filters are introduced in the pupil plane of the
illuminator, e.g. with a quadrupole-shaped or annular
transmission area. In a more complex case the same field
is printed several times. Several parameters can be made
35   to vary between the exposures, such as focus in the image
plane, illumination pattern, data applied to the SLM and
pupil filter in the pupil plane of the projection optics.

In particular the synchronised variation of the illumination and a pupil filter can give an increased resolution, most notably if the pupil has and a sector-shaped transmitting area and the illumination is aligned

5   so that the non-diffracted light intercepts an absorbing patch near the apex of the sector

Linearisation of the response

For linearisation of the transfer function from data

10   to edge placement here are essentially three ways to go:
- taking the non-linearity into account in the data conversion unit and generating an 8 bit (example) pixel values in the data conversion unit and use DACs with the same resolution to drive the SLM. This is shown

15   schematically in fig 8a, where R are relay signals and C are capacitors being provided on each matrix element on the SLM. The SLM is indicated by the dashed line.
- to generate digital values with fewer values, e.g. 5 bits or up to 32 values, and translate them to an 8 bit

20   value in a look-up table (LUT) and then feed the 8 bit values to the DACs.
- to use a 5 bit value and semiconductor switches to select a DC voltage that is generated by one or several high-resolution DACs. This is shown schematically in

25   fig 8b.

In either case it is possible to measure an empirical calibration function such that the response on the plate is linearised, when said function being applied at respectively the data conversion unit, the LUT or in

30   the DC voltages.

Which linearization scheme to use depends on the data rate, the precision requirements and also on the available circuit technology that may change over time. At the present time the data conversion unit is a

35   bottleneck and therefore it is not a preferred solution to linearise in the data conversion unit, neither to generate 8-bit pixel values. High-speed DACs are

expensive and power-hungry and the most appropriate
solution is to generate DC voltages and use switches. It
is then possible to use even higher resolution than 8
bits.

5

Description of a preferred pattern generator
        Referring to figure 6, a pattern generator comprises
an SLM 601 with individual and multi-value pixel
addressing, an illumination source 602, an illumination
10   beam scrambling device 603, an imaging optical system
604, a fine positioning substrate stage 605 with an
interferometer position control system 606 and a hardware
and software data handling system 607 for the SLM. For
proper functionality and ease of operation it also
15   contains a surrounding climate chamber with temperature
control, a substrate loading system, software for timing
of stage movement and exposure laser triggering to
achieve optimum pattern placement accuracy and a software
user interface.
20   The illumination in the pattern generator is done
with a KrF excimer laser giving a 10-20 nanoseconds long
light flash in the UV region at 248 nanometer wavelength
with a bandwidth corresponding to the natural linewidth
of an excimer laser. In order to avoid pattern distortion
25   on the substrate, the light from the excimer laser is
uniformly distributed over the SLM surface and the light
has a short enough coherence length not to produce laser
speckle on the substrate. A beam scrambler is used to
achieve these two aims. It divides the beam from the
30   excimer laser in several beam paths with different path
length and then adds them together in order to reduce the
spatial coherence length. The beam scrambler also has a
beam homogenizer consisting of a lens system containing a
set of fly-eye lenses that distributes the light from
35   each point in the laser beam from the excimer laser
uniformly over the SLM surface giving a "top-hat" light
distribution. This beam scrambling, homogenizing and

reduction of coherence is advantageous in all SLM
printers. Depending on the actual circumstances
implementations using beam-splitters and combiners,
diffractive elements, optical fibres, kaleidoscopes,

5   lenslet arrays, prisms or prism arrays or integrating
spheres can be used, as well as other similar devices in
combinations which split and combines the beams to create
a multitude of mutually incoherent light fields impinging
on the SLM.

10   The light from the SLM is relayed and imaged down to
the substrate on the substrate stage. This is done using
a Schlieren optical system described by Kück. A lens l_1
with the focal width f_1 is placed at the distance f_1 from
the SLM. Another lens l_2 with the focal length f_2 is

15   placed at the distance $2 \times f_1 + f_2$ from the SLM. The
substrate is then at a distance $2 \times f_1 + 2 \times f_2$ from the
SLM. At the distance $2 \times f_1$ from the SLM there is an
aperture 608 which size determines the numerical aperture
(NA) of the system and thereby the minimum pattern

20   feature size that can be written on the substrate. In
order to correct for imperfections in the optical system
and the substrate flatness there is also a focal system
that dynamically positions the lens l_2 in the z direction
with a position span of 50 micrometers to achieve optimal

25   focal properties. The lens system is also wavelength
corrected for the illuminating wavelength of 248
nanometers and has a bandwidth tolerance of the
illuminating light of at least ±1 nanometer. The
illuminating light is reflected into the imaging optical

30   system using a beamsplitter 609 that is positioned
immediately above the lens l_1. For a demagnification
factor of 250 and an NA of 0.62 it is possible to expose
pattern features with a size down to 0.2 micrometers with
a good pattern quality. With 32 levels from each SLM-

35   pixel the minimum gridsize is 2 nanometers.
        The pattern generator has a fine positioning
substrate stage with an interferometer position control

system. It consists of a moveable air bearing xy table 605 made of zerodur for minimum thermal expansion. A servo system with an interferometer position feedback measuring system 606 controls the stage positioning in

5   each direction. In one direction, y, the servo system keeps the stage in fixed position and in the other direction, x, the stage moves with continuos speed. The interferometer position measuring system is used in the x-direction to trigger the exposure laser flashes to give

10   uniform position between each image of the SLM on the substrate. When a full row of SLM images are exposed on the substrate the stage moves back to the original position in the x direction and moves one SLM image increment in the y direction to expose another row of SLM

15   images on the substrate. This procedure is repeated until the entire substrate is exposed.

The SLM images overlaps with a number of pixels in both the x and y direction and the exposure data pattern is locally modified in the overlap pixels to compensate

20   for the increased number of exposures that result in such overlap areas.

Variations in pulse to pulse intensity from the excimer laser is compensated by using two-pass exposure of the pattern where the first pass is done using a

25   nominal 90% intensity of the correct intensity. In the first pass, the actual intensity in each laser flash is measured and stored. In the second pass, the correct intensity for each SLM image exposure is then used based on the measured intensity values from the first pass. In

30   this way it is possible to reduce the influence from pulse to pulse intensity variations from the excimer laser by one order of magnitude.

The functionality of the SLM is described extensively elsewhere in this text. It has 2048 x 256

35   pixels with pixel size of 16 micrometers and it is possible to address all pixels within 1 millisecond. The SLM is rigidly mounted in a fine stage. This fine stage

is moveable 100 microns in the x and y directions with accuracy better than 100 nanometers between each flash exposure. The fine positioning of the SLM is used to correct for position inaccuracy of the substrate
5   positioning stage to further reduce pattern-stitching errors. In addition to the x-y positioning, there is also a rotational possibility of the SLM stage in order to expose a pattern on a substrate with an angle other than the one specified by the substrate stage coordinate
10   system. The purpose for such rotation is to create the possibility of incorporating substrate alignment feasibility for substrates with an already existing pattern where additional features shall be added. It is possible to measure the exact position of the substrate
15   on the stage after loading it using an off axis optical channel and/or a CCD camera looking through the lens to determine the system coordinates for a number of alignment marks existing on the substrate. During exposure, the stage position is then corrected in the x-
20   and y-directions based on the measured positions of the alignment marks. Rotational alignment is achieved by using the stage servo system to follow the rotated coordinate system and also rotating the SLM fine stage as described. The possibility of rotating the SLM makes it
25   also possible to write in a distorted coordinate system, such as to compensate for subsequent warpage of the pattern.

An arbitrary data pattern of an arbitrary format is transformed into a compressed rasterized pixel map with
30   32 (5 bit) gray levels per pixel in a pattern rasterizer 610. Since the grayscale steps of an exposed pixel is not linear in response to the voltage applied to the pixel electrode, the input data is linearized in a pixel linearizer 611 so that the 32 gray levels correspond to a
35   uniform increase in exposure dose for each successive level. This is done using 8-bit digital to analog converters (DAC) 612 where each gray level from the pixel

map selects a voltage from the DAC's according to a
previously empirically calibrated linearization function.
An additional offset in the choice of analog level from
the DAC's is made using a lookup table where each value
5   corresponds to an SLM pixel and each such value corrects
for anomalies of the corresponding pixel. The calibration
values in the lookup table are generated using an
empirical calibration procedure where a series of test
patterns are sent to the SLM and the resulting exposed
10   patterns are measured and used for individual pixel
correction. This means that each gray level in the pixel
map selects an analog voltage generating a pixel
deformation for every corresponding SLM pixel to give the
correct exposure dose.

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References

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Kück 1990: European patent EP 0 610 183
20   Sandström et al. 1990: European patent EP 0 467 076

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